Automotive Sector

Electrical and Electronic Components in the Automotive Sector: Economic and Environmental Assessment*

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Abstract

Background, Aims and Scope. Automotive electrical and electronic systems (EES) comprise an area that has grown steadily in importance in the past decade and will continue to gain relevance in the foreseeable future. For this reason, the SEES project (Sustainable Electrical & Electronic System for the Automotive Sector) aims to contribute to cost-effective and eco-efficient EES components. Scenarios for the recovery of automotive EES are defined by taking into consideration the required improvements in EES design and the development and implementation of new technologies. The research project SEES is funded by the European Commission (Contract no. TST3-CT-2003-506075) within the Sixth Framework Programme, priority 6.2 (see <www.sees-project.net> for more information). This paper presents the findings of an assessment of the environmental and economic improvements for automotive EES from a system perspective, taking into account all life cycle steps.

Methods. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) case studies have been employed within the SEES project to define optimum design and end-of-life scenarios. These case studies have been applied to two selected EES components: an engine wire harness and a smart junction box, both manufactured by LEAR and assembled in an existing Ford car model. The component design has a significant impact on the product system and its processes, including its use and end-of-life (EOL) phase. For each of the analysed components, two potential design alternatives have been compared with the original design, based on designers' recommendations from the status quo scenario results. These include the use of alternative wiring systems with a reduced copper content (flat flexible cable), lead-free solder alloys and new fixation mechanisms to facilitate disassembly. The overall EOL scenario determines the technologies of processes that must be modelled within the EOL phase of a product system. The analysed end-of-life scenarios include: status quo car recycling and two alternatives: 1. disassembly for specific EES component recycling; 2. advanced post-shredder recycling of shredding residues. The influences of the different design and EOL treatment scenarios on the LCA and LCC results have been analysed.

Results. The most dominant life cycle phases for the LCA results are manufacturing (including raw material extraction and manufacturing of materials and components) and the use-phase. Similarly, manufacturing was the predominant phase during the LCC study. Disassembly costs were shown to be significant during the EOL phase. Among the analysed design alternatives, the highest environmental improvement potential were gained from the use of alternative wiring systems with reduced weight and copper content, but with slightly increased life cycle costs. Smaller differences of the results were determined for the different end-of-life scenarios.

Discussion. The results of the EOL scenario depend on the component in question. The influence of variations in process data, model choices, e.g. which LCIA model was used for calculating the Human Toxicity Potential (HTP), which inventory data for copper production was used and other variables have been assessed in the sensitivity analysis. The sensitivity analysis demonstrates a strong dependency of results for HTP on the selected model. The presented results are based on a public report of the SEES project. The study has undergone a critical review by an external expert according to ISO 14040, § 7.3.2.

Conclusions. The environmental impacts during the life cycle of the analysed products are generally most strongly influenced by material production and the use phase of the products. In comparison, improvements during the EOL phase have only a very limited potential to reduce environmental impacts. The studied design changes displayed clear environmental advantages for (lighter) flat, flexible cables. Whereas, the lead-free solder design alternatives showed a slight increase in some environmental impact categories. The application of these design changes has been limited in some cases by technical issues.

Recommendations and Perspectives. Focussing only on end-of-life improvements cannot be recommended for automotive EES products. A life-cycle perspective should be utilised for assessing improvements in individual life cycle stages of a product. The presented results will be an input for Eco-design guidelines for automotive EES, to be developed at a later stage within the SEES project.

Keywords: Automotive electrical and electronic components; design alternatives; dismantling; end-of-life scenarios; LCA case studies; LCC case studies; recycling; smart junction box; wire harness

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Introduction

Automotive electrical and electronic systems (EES) comprise an area that has grown steadily in importance in the past decade, increasing by 5–8% in value per year, a trend that is forecasted to continue well into the future. (Golm et al 2002). For this reason, the SEES project (Sustainable Electrical & Electronic System for the Automotive Sector) aims to contribute to cost-effective and eco-efficient EES. Scenarios for the recovery of automotive EES have been defined by taking into consideration the required improvements in EES design and the development and implementation of new technologies. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) case studies have been conducted in order to assess environmental and economic improvements for automotive EES from a system perspective, taking into account all life cycle steps.

Within the SEES project, the various EES for automobiles have been analysed and qualitatively evaluated (SEES D1 Report). Based on this information, representative EES components were chosen to undergo an environmental and economic assessment. The components under investigation are an engine wire harness (WH) including a wired junction box for power and signal distribution in the engine compartment and a passenger smart junction box (PSJB) located in the passenger compartment, for electronically controlling and switching functions. The WH is representative of other kinds of car wire harnesses (in other car compartments) for distribution of electric power and electronic information. The total mass of all wire harnesses contributes to a high proportion of the total mass of EES components. Similarly, the selection of the PSJB as the second component was based on it being a typical example of a junction box for electronic control units (containing printed circuit boards) and electrical switches.

1 Goal and Scope

The goal of the studies is to determine and compare the potential environmental and economic impacts of alternative product system scenarios and assess the significance of improvement potentials in design and recycling. Therefore, different design and end-of-life scenarios have been defined (see Section 3) for analysis using LCA and LCC methodologies. An independent review according to ISO 14040, § 7.3.2 has been conducted by Prof. Walter Klöpffer.

One WH/ PSJB, with specified functionality (reference product from LEAR) and assembled in a middle-class Ford car model with an assumed use phase of 150,000 km in 12 years is defined as the functional unit. The duration and mileage of the use phase is based on a common assumption for middle-class passenger cars (Ridge 1997). All data refer to the processing, use phase and disposal of the reference flow. The material data for the components production are based on average values for diesel and gasoline engine options (note: different versions of WH and PSJB exist depending, for example, on the engine type). For the use phase, a fuel mix of 44% diesel and 56% gasoline engines has been assumed; in proportion to the share of new passenger car registrations by engine type in Europe in 2003 (ACEA 2003). The fuel consumption is assumed to be 5.4 l per 100 km for diesel engines and 7.0 l for gasoline engines. This assumption is based on an average fuel consumption for the different engine options offered for the Ford car model under consideration. Allocation of fuel consumption from the whole car to the single car component has been based on an incremental approach according to (Ridge 1997).

2 Methods

The following impact categories based on CML 2001 characterisation and normalisation factors (Europe EU-15) (Guinée et al. 2002) have been calculated: Depletion of abiotic resources (ADP), Climate change (GWP), Photo-oxidant formation (POCP), Eutrophication (EP), Acidification (AP) and Human Toxicity (HTP). Due to fundamental scientific doubts in the project team, different approaches for HTP have been evaluated.

LCC has been applied in order to assist product designers and partners from industry. Specific LCI and cost data have been applied to the foreground system, whereas generic LCI and price data have been applied to the background system. In general, foreground processes can be influenced by the producer and are covered by specific data from SEES partners. LCC results in terms of costs and revenues for manufacturing including material production, use and EOL are shown from the point of view of the following actors: producer of EES and cars, user of EES in cars and recycler of EES in cars based on a discounting rate of 5%.

Different design and end-of-life (EOL) scenarios for each component have been evaluated in the LCA and LCC case studies. The analysed design alternatives for the WH and PSJB are based on EES designers' recommendations from the status quo scenario (Design I) results. The design alternatives for both EESs include material based changes (Design II.1) as well as fastener-related alternatives (Design II.2) to facilitate disassembly.

2.1 Design alternatives

2.1.1 Design II1, WH: Reduced copper content by flat flexible cable

The striving for weight minimisation and maximum consumer acceptance (e.g. comfort), have driven changes in material selection in automotive applications (**Table 1**). An example is the substitution of conventional round (copper) wiring by flat flexible cable (FFC) as described in (SEES 2005). The most important factors in the selection of flat cable in wire harnesses include: the potential weight and space savings due to its higher transfer capacity for the same wire section as well as its automation potential. Whilst the introduction of flat cables into new EES equipment is still in the development stage, it is becoming important as the pressure increases to reduce component size and weight. In many applications it can provide improved reliability and operational efficiency due to its unique characteristics. With flat cable, a system or functional approach can be easily applied to interconnections which will provide efficient, integrated, and optimized assemblies for signal and power transmis-

Table 1: Material composition of WH in relation to analysed Design Alternatives

	Design I Original Design		Design II.1 (Flat Flexible Cable)		Design II.2 (Hook & Loop Tapes)	
	Mass [g]	Mass [%]	Mass [g]	Mass [%]	Mass [g]	Mass [%]
Copper	3539.7	48.2	2293.7	39.9	3539.7	49.2
Ferrous metals	149.5	2.0	149.5	2.5	149.5	2.1
Other non-ferrous metals	21.5	0.3	21.5	0.4	21.5	0.3
(Thermo)plastics	2339.3	31.9	2138.2	35.6	2186.1	30.4
Others (incl. Elastomers)	1293.3	17.6	1298.9	21.6	1292.1	18.0
Total [g]	**7343.4**		**6001.8**		**7189.0**	

sion. While flat flexible cables are manufactured in many different ways, e.g. etched, extruded, laminated, woven, pre-insulated, etc., the extruded flat cable (FFCe) has been chosen for these studies as the design alternative. A theoretical substitution of 50% of the original round wiring by flat flexible cable has been assumed for this scenario, although it has been limited in some cases by technical issues. Such an approach reduces the total weight and the relative copper content of the WH.

2.1.2 Design II2, WH: Use of hook and loop tapes as alternative type of joining to the car

In light of the upcoming requirements regarding material recovery of EOL vehicles, the improvement of disassembly operations might be a theoretical option for countries with low labour rates for reuse. In the specific case of the WH, the faster dismantling times through the use of hook and loop tapes could offer advantages during the end-of-life processes in those countries (SEES 2005). Additionally, this would facilitate a faster and efficient assembly process within the production phase. The improved design suggested (see Table 1) aims at reducing the number of plastic clips along the WH configuration to reduce assembly time as well as disassembly service time. The new design will fix the 'loop' tape along the cable ties and is used to attach the WH to the 'hook' route along the automobile surface so as to hold the WH in place. For this design alternative, the proposed variation assumes the substitution of 80% of the original routing and fixation mechanisms (channels, clips, adhesive tapes) by the deployment of hook and loop tapes. It should be noted that the assumed general improvements in dismantling times by various Design-for-Disassembly actions are mainly theoretically, but not statistically valid in practical tests.

2.1.3 Design II1, PSJB: Use of lead-free solder alloys

Due to general activities also in other sectors, automotive electronics suppliers have begun to investigate the potential use of lead-free solders. For the substitution of the solder, the lead-free tin-silver (SnAg) alloy was selected. The high stability of this alloy is supplemented by a good temperature cycling and creep resistance having a more uniform microstructure than other conventional alloys (ZVEI 2000). The application of lead-free solder is associated with increased energy needs (estimated to be 21% higher than conventional lead alloys) due to higher melting temperatures of the alloys for soldering processes.

2.1. Design II2, PSJB: Potentially easy to dismantle fasteners of the housing of the PSJB

This design option is based on efficient and, therefore, faster dismantling times via the deployment of connection elements or joints that are easy to separate. The reduction in the number and complexity of the disassembly steps leads to a reduction in the second level disassembly time. The total dismantling time for separating the PSJB cover from the printed circuit board was reported as 80 sec for Design I, a time which excludes extracting the inserted components (relays and fuses) from the populated board. The mass of the product remains almost equal. It is assumed that the fasteners consisting of PP GF like the covers of the PSJB are substituting the screws. This improvement may lead to a separation of box and printed circuit boards, if the component is disassembled out of the car, e.g. for re-use. Again, the assumed theoretical improvements in dismantling times might not result in practical improvements.

2.2 End-of-Life (EOL) scenarios

2.2.1 EOL0, EOL0a (status quo)

Following fluid and airbag removal, the whole car undergoes the shredder process with the EES component in question ending up in the different shredder output fractions that can be recycled – e.g. iron fraction – or disposed of in landfill (EOL0) or (depending on the existing infrastructure and legislation) incinerated (EOL0a) – e.g. Shredder Residue (SR).

The non-ferrous and ferrous metals are separated in the shredder and recycled separately, albeit with a certain level of material mixture. Typically, the plastics and synthetic rubbers end up in the SR that is either sent to a landfill or incineration with energy recovery.

In estimating the amounts of each material fraction that are separated into the different shredder output fractions, assumptions concerning the efficiency of material separation in the shredder have been made: 98% of the ferrous metal input ends up in the ferrous fraction for steel recycling. As much as 80% of the copper material is separated and sent to smelters for recycling (after further separation of the mixed non-ferrous fraction for specific recycling) and 100% of the plastics, elastomers and other materials end up in the SR. Assumptions on the separation rates are based on averages from literature values (Reinhardt & Richers, 2004), (Lohse et al. 2001), (Ebersberger 1995) and estimations from practical trials conducted by project partner Müller-Guttenbrunn

(shredder company). However, not all the assumptions/estimations have been endorsed by all of the project partners. In EOL0, it is assumed that the total SR containing non-metals including plastics is sent to landfill. The disposal practice of the SR before 01.06.2005 (eventually mixed with filter dust) has been predominantly landfilling (ca. 80% in Western Europe). Only small amounts of SR (ca. 20%) have been actually co-incinerated in domestic waste incineration plants or otherwise treated for energy recovery (e.g. in cement kilns) (ICGS 2004). The recovery of energy from SR without treatment, e.g. in the municipal incinerator route is analysed in EOL0a.

2.2.2 EOL1: Disassembly of the WH/PSJB and advanced mechanical and chemical recycling

In scenario EOL1, a possible situation is examined whereby, the PSJB is disassembled and the engine WH is partly disassembled before the automobile is shredded. The easily accessible part of the engine WH (ca. 50% of the harness weight and the wired junction box) is disassembled and treated separately from the other materials in the car. Results from the SEES project indicate that the disassembly of the complete engine WH is neither economically feasible nor necessary, since its recovery is more easily achieved after shredding, if required at all (SEES 2005). Nevertheless, the initial driver for the investigation had been the improved copper purity and the improved recycling rate of precious metals from the electronic printed circuit board of the PSJB (conventionally, precious metals are lost in the SR) which could yield potential benefits via partial disassembly. The disassembly employs manual and destructive methods. After disassembly, the components are mechanically recycled into various size fractions and material separation. The precious metal containing fractions recovered from the printed circuit boards are then chemically recycled for their metal values. For further details of the mechanical and chemical recycling technologies, see (SEES D7 Report 2005).

2.2.3 EOL2: Car shredder and advanced post-shredder recycling

The whole car undergoes the shredder process without prior dismantling of the WH and the PSJB (as in EOL0/ EOL0a). In addition to the separation and recycling of the ferrous and non-ferrous metal fractions, the SR is sorted and mechanically recycled using innovative technologies, which were analysed within the SEES project (SEES 2005). Finally, the following material fractions are separately collected: processed fines (metal fraction, plastic-rich fraction and dust); processed soft fraction (plastic pellets, organic fibres, dust); cable fraction, PCBs and mixed metals; ferrous metals (for direct sale); non-ferrous metals (for direct sale); plastics. All Fe and non-ferrous metals are recycled with some of the plastic fractions being recycled and some recycled via incineration with energy recovery. Wood and the organic fractions are used for energy recovery and the dust is incinerated. This reduces the amount of SR that must be disposed of and increases recycling and recovery of metals and plastics from the car.

3 Results

3.1 Analysed design alternatives: WH

The LCA results are generally dominated by the manufacturing phase (incl. material and components production) and the use phase, whereas the impact of the EOL processes is very low (**Fig. 1**). Credits are given for recycled materials, since primary resources are saved due to the recycling of materials. The dominance of the use phase for ADP, GWP,

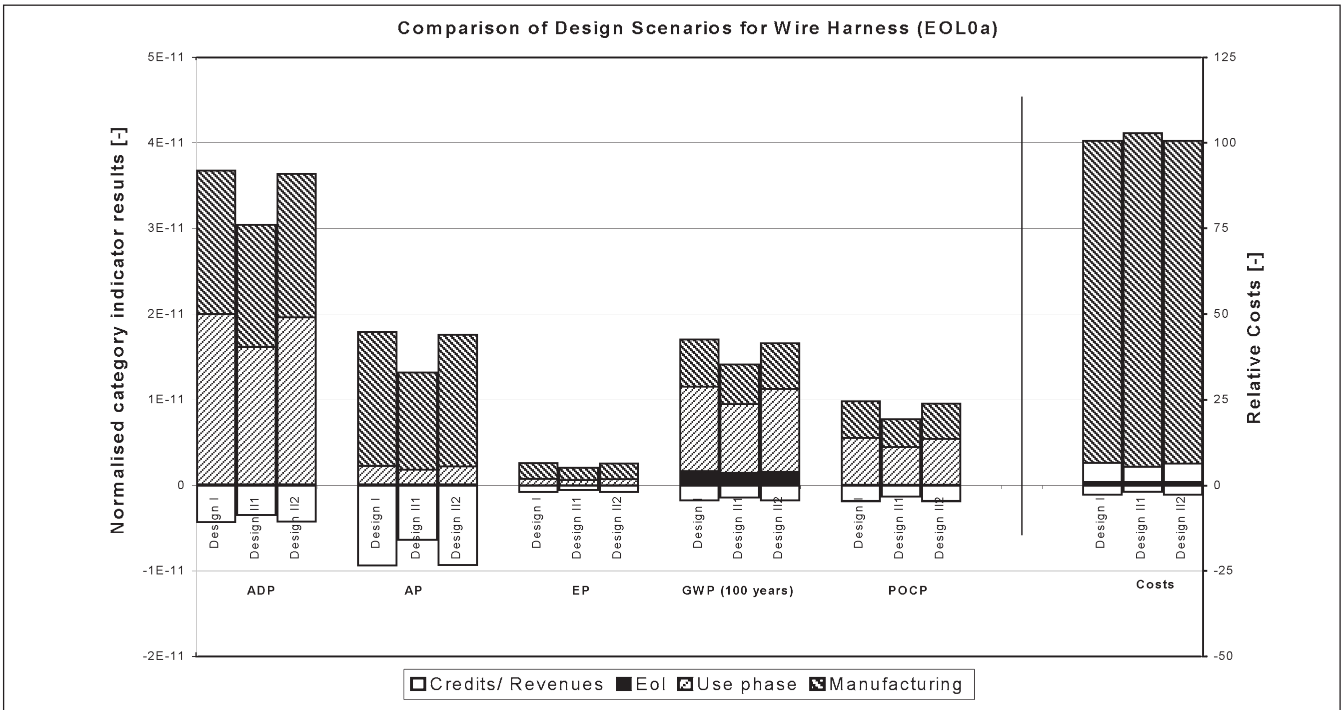

Fig. 1: LCA results for analysed Design Alternatives for WH, EOL0a

POCP is due to the allocated fuel consumption caused by the weight of the WH, which results in depletion of energy resources, emission of volatile organic compounds (VOC) and carbon dioxide as the driving substances. The dominance of the manufacturing phase for AP and EP is mainly due to copper production, which accounts for ca. 63% of the AP, 44% of the EP. This shows that the life cycle stages from the raw material extraction to the material production is much more relevant on the results than for the actual manufacturing processes for the WH at the EES producer (the later assembly process at the vehicle manufacturer level is negligible). The alternative Design II1 (flexible flat cable) has considerably lower potential environmental impacts in all analyzed categories compared to the status quo Design I. This is due to the reduced weight (ca. –18%) which positively influences the impacts allocated during the use phase and may be explained by the reduced material production for manufacturing of the WH. The reduced relative copper content of the Design II1 results in the strongest relative reduction in the impact category AP which is dominated by the copper production. Design II2 (hook & loop tapes) has no significant effect on the LCA result. The life cycle costs are significantly influenced by manufacturing (more than 90% of the total life cycle costs) than is the case for the LCA results. The costs of the use phase again correlate to the different weights of the alternative designs. During the manufacturing phase, the Design II1 has some increased costs despite the reduced copper mass (see Table 1) (higher costs of FFC compared to round cables in some applications) which exceeds the cost savings accrued during the use phase. Consequently, the revenues obtained fractions for recycling are also lower for Design II1 (reduced copper content). Manufacturing costs of Design II2 are almost identical with the Design I. Since the differences between the calculated results for the analysed design alternatives are small, the SEES project placed emphasis on sensitivity analyses to assess the influences of estimates and, therefore, robustness of results, see Section 3.5.

3.2 Analysed design alternatives: PSJB

The values for the life cycle stage manufacturing (including raw material extraction and manufacturing of components), EOL and credits or revenues are influenced by design changes. In general, the most dominant life cycle stages are manufacturing and use of the PSJB, whereas the EOL stage has a less significant impact on the total life cycle. Since the weight of the PSJB is not appreciably influenced by the design alternatives, the use stage is not significantly affected by the analysed design alternatives. The calculated normative indicator results for ADP, AP, GWP and POCP are higher during the manufacturing stage for Design II1 (lead-free solder) compared to Design I. The higher results in the impact category AP agree with results of (Itsubo et al. 2004). Potential impacts incurred by the raw material production for lead-free solder result in higher values of AP and GWP, since energy consumption in lead production is less than that for other alloy components. Design II1 is characterized by three affects compared to Design I. These are: the production processes for the analysed solder paste, higher energy consumption caused by the properties of the analysed solder paste and the reduced mass caused by the densities of the analysed solder paste. The calculated results in the EOL stage are not affected by the inventory data used for the solder paste production in the SEES project. Therefore, no conclusions on the actual end-of-life behaviour of the different solder alloys can be made. A more detailed analysis of the EOL stage has been reported within the EFSOT-project, see for example (Deubzer et al. 2004), (EFSOT 2004). The need for more research on EOL processes and inventory data, to enable an evaluation of the effects and the behaviour of Pb or Ag in incineration or landfill processes is evident. With the given assumptions and limitations, Design I performs better in all analysed categories from an environmental point of view. The total LCC for Design II1 are slightly higher, as a result of the higher purchase price for lead-free solder paste. The comparison of Design II2 (PP-GF fastener) with Design I shows slightly reduced values in the categories ADP, AP, GWP and POCP. The covers made of PP can be theoretically disassembled and recycled in a pure way (assuming that there is a market for the recycled material). Therefore, the credits for material recycling are assumed to be higher in AP and GWP and almost identical for the other impact categories. They are resulting from second level disassembly and are given for pure recycling of the PSJBs covers (PP 20GF). There is almost no difference for the manufacturing cost. Only material costs have been analysed. It is assumed that the same mass of PP is necessary to integrate the fasteners for a second level disassembly, no screws are necessary.

3.3 Analysed EOL scenarios: WH

The shift from using landfills for SR (EOL0) to SR incineration (EOL0a) results in higher GWP due to CO_2 emissions during incineration (**Fig. 2**). In total, (including the credits based on the substitution of electric power production in a gas and steam power plant) the EOL0a has slight disadvantages in GWP but advantages in ADP, AP, EP and POCP. In some countries, the legal framework does not permit landfilling of SR and EOL0a is therefore assumed as the basis for further comparison.

The alternative scenario EOL1 has advantages in relation to the current scenario EOL0a in the total results in all impact categories because of the higher credits given for the larger material amounts which have been recycled. However, the advantages are insignificant when considering the whole life cycle. The revenues for the obtained recyclable fractions increase accordingly. The costs of EOL treatment are higher for EOL1 because of the additional machinery inputs and disassembly costs for EOL1. For Design II2 (hook & loop tapes) in the EOL1 scenario, the reduced disassembly time results in reduced EOL costs. In summary, the EOL1 scenario is still more cost effective than EOL0a because of the increased revenues and cost savings achieved via the reduced volumes of SR going to incineration.

EOL2 has advantages in relation to the current scenario EOL0a in all impact categories. Credits given for the larger material amounts which have been recycled after post-shredder treatment are higher in EOL 2. On the one hand, the

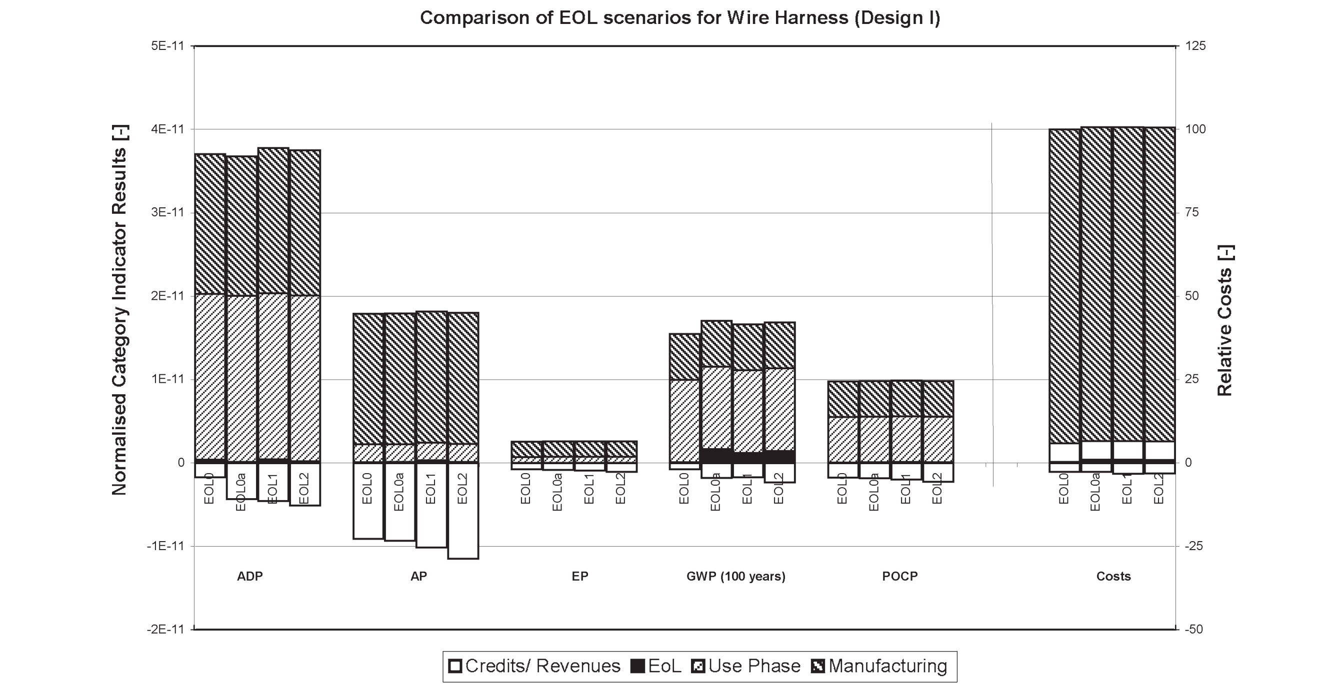

Fig. 2: LCA results for analysed EOL Scenarios for WH, Design I

revenues for the obtained recyclable fractions increase accordingly to the LCA results, whereas the costs of EOL treatment were higher for EOL2 because of the additional machinery effort. To summarise, the EOL2 scenario is still more cost efficient than EOL0a because of the increased revenues and saved costs for reduced SR amount going to incineration. EOL2 (Post-shredder treatment) is even better than EOL1 (dismantling) for the given credits in all analysed environmental impact categories. The post-shredder recycling processes in EOL2 improve the recycling and recovery of the total copper, plastics and steel content of the WH. In contrast, the EOL1 scenario only improves the recycling and recovery of the disassembled WH. Since the WH from the engine compartment can only be partly disassembled in a reasonable time, as about 50% of the original cable fraction of the WH remains in the shredder recycling path in EOL1. Therefore, EOL2 yields better environmental results than EOL1 for this component. Moreover, the differences resulting from the various EOL scenarios remain small compared to the differences when changing the design. The revenues for the obtained recyclable fractions increase accordingly to the increasing credits. Revenues of EOL2 are higher than EOL1. Since the differences between the analysed EOL scenarios are small, the SEES project placed emphasis on sensitivity analyses.

3.4 Analysed EOL scenarios: PSJB

The values for the Life Cycle stage EOL and credits or revenues are influenced by changing EOL scenarios. In general, the most dominant life cycle stages are manufacturing and use phases of the PSJB, whereas the EOL stage has a smaller contribution to the impacts of the total life cycle. Comparing the LCA results of EOL0a to EOL0, credits for ADP, AP, GWP are higher for EOL0a. This is due to the energy recovery of the incineration process of SR. If the credits are totalled for all the impacts of the life cycle, EOL0a is better in ADP, AP and GWP. From an environmental point of view, EOL0a is better than EOL0. The costs for EOL0a are higher than for EOL0. This is due to the assumed costs of 50 €/ton for SR sent to landfill, whereas the costs for SR sent to incineration is about 150 €/ton (Reinhardt & Richers, 2004). Revenues are almost unaffected by the differences in these scenarios. In general, EOL0 is more cost effective due to the previously low costs associated with landfilling this material. Comparing the LCA results of EOL1 to EOL0a, higher credits are calculated for ADP, AP, EP, GWP and POCP for EOL1. This is due to credits for the recycling of polyolefins, PA and energy recovery (ADP), credits for the recycling of polyolefines (AP, EP, GWP, POCP) and a higher mass of copper.

The calculated indicator results in ADP, AP, EP, GWP and POCP are higher for EOL1 in relation to EOL0a. These higher values are based on the higher energy consumption for the mechanical recycling processes in EOL1. If the credits are totalled for all the Life Cycle impacts, EOL 1 is better in AP and equivalent to the calculated results of the other impact categories. Comparing the results from an economic point of view, the total LCC are higher for EOL 1 due to the disassembly costs which cannot be offset by higher revenues.

The calculated credits in ADP, EP, GWP and POCP are almost identical for EOL2 compared to EOL0a. Credits in EOL2 for AP are higher, because the recovered mass of copper is higher in EOL2. Most of the plastic fraction is incinerated, leading to similar credits as in EOL0a for energy recovery. The differences between EOL2 and EOL0a arise solely from higher credits of EOL2: EOL2 is environmentally advantageous in AP. Comparing the calculated results from an economic point of view, there are no significant differences between EOL0a and EOL2 for the total LCC.

The results lead to higher credits in the categories ADP, AP and GWP in EOL1 compared to EOL2. This is caused by credits for the recycled fraction of PA, polyolefines (ADP, AP, GWP) and copper (GWP). The environmental impacts resulting for the EOL processes are lower in EOL2 compared to EOL1 in all categories. This is due to the lower energy consumption in EOL2 and substances used for chemical recycling in EOL1. In total, the impacts are lower in EOL1 if there is a market for the recycled plastic fractions. The total LCC shows better results for EOL2 due to the high disassembly costs in EOL1.

3.5 Sensitivity analyses

In order to use LCA as a tool for decision-making, information on the robustness of the results is needed (Guinée et al. 2002). The influence on the results of variations in process data (separation rate for copper in EOL1, Fuel Reduction Value (FRV) for modelling the use phase (Ridge 1997)), model choices (LCIA: methods for calculating HTP) and other variables (inventory data for copper) is assessed.

Preliminary results (see (SEES 2005) have indicated that copper production plays a central role in the environmental performance of the components under examination in the SEES project, especially for AP. For this reason, it is critically important to consider the input data used and the associated boundary conditions, assumptions and methodology. The actual amount of secondary copper used in the products under examination is not known and quite possibly varies over time if suppliers change their sources of materials. Therefore, an assumption of the European average is appropriate for used inventory data. According to a report from the European Copper Institute, 40% of Europe's annual demand for copper is supplied by recycling (European Copper Institute 2001). The EcoInvent data set 'at regional storage' has been used for calculating the final results, because the inclusion of secondary copper seems to meet the production reality better than other available inventory data. However, changing only the used inventory data set for copper production could have a large influence on the overall LCA results (especially AP, HTP which are dominated by copper production).

Human Toxicity is currently the most discussed impact category, e.g. (Huibregts et al. 2005), (Heijungs et al. 2004), as different methods for calculation may reveal different results. The impact of Human Toxicity is local rather than global, although Human Toxicity might be a relevant impact category for the evaluation of electrical and electronic components because of toxic substances that are regularly involved in the production of these products. Therefore, two LCIA models have been used for calculating and comparing results: CML2001, see (Guinée et al. 2002) and IMPACT2002+, see (Jolliet et al. 2003). The most important difference in the results of the two HTP models is the weighting of the substance categories. These differences are obvious from the characterization factors of the two models. The results show that the calculated Human Toxicity Potential (HTP) strongly depends on the selected model and that only a few processes with high data resolution actually contribute to the calculated HTP. In comparison to the other impact categories, the HTP results should be considered more unstable. Therefore, any proposed design changes should not be based solely on a reduced HTP if it results in a negative impact on any of the other analysed impact categories and with no improvements in other impact categories. Fortunately, for the analysed alternatives, theoretical HTP improvements have always been accompanied by improvements in other impact categories. The HTP values (CML2001) are not presented in the figures.

4 Interpretation and Discussion of Final LCA/LCC Results

The results of the interpretation phase lead to a number of judgements relating to the quality and the robustness of the findings of the Inventory Analyses and Impact Assessment (Guinée et al. 2002). The presented results are based on the (SEES D7 Report 2005). According to ISO 14040, the results of the life cycle inventory analyses and life cycle impact assessment are summarised and discussed as a basis for conclusion, recommendations and decision making in accordance with the goal and scope definition. From the presented results, the following can be concluded:

- The dominant life cycle phases from the environmental point of view are firstly, the manufacture of materials and components and, secondly, the use phase. EOL processes have a low impact on the LCA results (mostly << 10%), but a large influence on the credits for the obtained recyclable fractions – in particular copper.
- The LCC results are clearly dominated by the manufacturing of materials and components, particularly for the PSJB. This seems to be the most promising life cycle stage for cost reductions. The decision to select one design option would be driven primarily by costs rather than by environmental results.
- Material production, namely the production of copper, has a strong influence on the overall LCA results, especially for the AP. The reduction of copper content could be a potential for environmental savings. Likewise, sorting / recycling of copper has a major influence on the LCA results (credits) and LCC results (revenues) and, therefore, on the environmental and economic performance. However, this conclusion depends heavily on the validity of the data used for copper production, which may not reflect the latest technologies.
- The analysed design alternatives for the WH show:
  - A clear environmental improvement in the case of Design II1 (FFC), but no environmental business case (Schmidt 2003) for some applications.
  - No significant environmental improvement in the case of Design II2 (hook-loop-tapes), but a slight cost reduction which becomes more relevant for disassembly (EOL1) if such EOL strategy is followed.
- The analysed design alternatives for the PSJB show:
  - The mentioned limitations in assessing the end-of-life behaviour of the different solder alloys do not enable a clear identification of the environmental advantages of Design I against Design II1. Although Design I performs better in all analysed impact categories. For a more detailed analysis of all the affects from Pb and Ag in manufacturing and EOL processes, results from (EFSOT 2004) should be taken into account. Research for reliable in-

ventory data is still necessary. The total LCC for Design II.1 are slightly higher caused by higher prices for lead-free solder paste (no environmental business case).
  - Design II2 is slightly better than Design I for EOL1. There is almost no difference for the manufacturing cost: only material costs are analysed for the different fasteners (plastic fasteners instead of screws).
- The analysed alternative EOL scenarios for the WH and the PSJB show:
  - An environmental and economic improvement for both EOL1 and EOL2 when the credits and revenues for the secondary material are taken into account.
  - In the case of the WH, the EOL2 (post-shredder treatment) would be more environmentally recommendable because the WH from the engine compartment could be only partially disassembled, resulting in reduced environmental and economic benefit from the EOL1 scenario.
  - More efficient sorting and recycling technology hold improvement potential.
- The analysed, alternative EOL scenarios for the PSJB show:
  - From an environmental point of view, EOL 1 is better than EOL0/ 0a. The total Life Cycle Costs are higher for EOL 1, due to increased disassembly costs.
  - EOL2 is better than EOL0 and EOL0a, but slightly worse than EOL1 in the environmental evaluation. There are no differences between EOL0a and EOL2. In contrast, EOL2 shows better results compared to EOL1 for the total LCC. A possible material recycling might lead to higher revenues at the same process line.

The following limitations of the presented results should be considered:

- HTP results are less reliable than other impact categories, this was shown in the sensitivity analyses.
- The inventory data used for copper production has a strong influence on the overall LCA results, which has been shown in the sensitivity analyses.
- For the analysed theoretical design alternatives, which are not actually produced, some assumptions had to be made. Where no specific manufacturing data was available, it has been estimated from the manufacturing of the status quo design.
- LCC results could not be normalised on European GDP basis, because of confidentiality reasons for data from industry partners and are therefore expressed as relative cost.

5 Conclusions

The environmental impacts during the life cycle of the analysed products are generally most strongly influenced by material and components production and the use phase of the products. In comparison, improvements during the EOL phase have only a very limited potential to reduce environmental impacts. The studied design changes displayed clear environmental advantages for (lighter) flat flexible cables, while showing a slight increase in some environmental impact categories for the chosen lead-free solder design alternatives. However, end-of-life behaviour could not be adequately included. There is only limited room for an environmental business case.

6 Recommendations and Perspectives

Focussing only on end-of-life improvements cannot be recommended for automotive EES products. A life-cycle perspective should be utilised for assessing improvements in individual life cycle stages of a product. The presented results will be employed in the development of Eco-design Guidelines for automotive EES.

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